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OPTIMUM ROUTE PLANNING AND SCHEDULING FOR UNMANNED AERIAL VEHICLES

by

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New threat perceptions have extended the sense of self-defense to include preemptive strikes if a threat is going to occur. For its part, the military should have high Intelligence, Surveillance, and Reconnaissance (ISR) capabilities to implement this strategy. UAVs play an important role as the most effective way of providing high quality ISR in today's modern wars. The route planning of UAVs is the most critical and challenging problem of wartime.

This thesis will develop three algorithms to solve a model that produces executable routings in order to dispatch three Unmanned Aerial Vehicles (UAV) to complete 20 different missions in different locations. These algorithms seek to maximize the bonus points are paired with the targets, representing the priority of the missions. By this definition, the problem can be classified as a Multiple Tour Maximum Prize Collection Problem (MTMPC). MTMCP is closely related to the classical Traveling Salesman and Vehicle Routing Problems with the difference that not all nodes can be visited in the available time. Each node is assigned a bonus point value representing the priority of that mission, and the objective of the MTMCP is to determine the nodes to be visited to maximize the collected bonus points.

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LIST OF ACRONYMS AND ABBREVIATIONS

ATO	Air Tasking Order
BDA	Battle Damage Assessment
CVRP	Capacitated VRP
EO	Electro-Optic
EW	Electronic Warfare
FAA	Federal Aviation Administration
HALE	High-Altitude Long Endurance
HVAA	High Valued Air Assets
IR	Infrared
ISR	Intelligence Surveillance and Reconnaissance
JSEAD	Joint Suppression Of Enemy Air Defenses
LALE	Low-Altitude Long Endurance
MALE	Medium-Altitude Long Endurance
MDVRP	Multiple Depot VRP
MTMCP	Multiple Tour Maximum Collection Problem
MTSP	Minimum Traveling Salesman Problem
NCW	Network Centric Warfare
NEC	Network Enabled Capability
NM	Nautical Miles
OP	Orienteering Problem
PVRP	Periodic VRP
SAR	Synthetic Aperture Radar

SDVRP	Split Delivery VRP
SVRP	Stochastic VRP
TOP	Team Orienteering Problem
TSP	Traveling Salesman Problem
VRP	Vehicle Routing Problem
VRPPD	VRP with Pick-Up And Delivering
VRPTW	VRP with Time Windows
UAV	Unmanned Aerial Vehicle
UAS	Unmanned Aircraft System

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I. INTRODUCTION

This study developed an executable routing model in order to dispatch three identical Unmanned Aerial Vehicles (UAV) from the same base to complete different missions in different locations. The model maximized the bonus points that were given based on the priority of the missions. This problem is similar to an Orienteering Problem (OP) and is closely related to tour problems such as the Traveling Salesman Problem (TSP) as well as some Network Design Problems. Similar to the problem of this study, these problems deal with a set of points in a two-dimensional plane, a starting point (depot), and a time or distance constraint. The objective is to find a tour, starting at the depot, that visits as many destinations as possible within the given endurance time to maximize the bonus points at those destinations.

The goal of this study was to develop an optimal route-planning model for Unmanned Aerial Vehicles. At the beginning of the study, the authors suggested three different algorithms for their case, which has 20 targets and three UAVs. Realizing that they could not find the exact solution using the Solver add-in in Microsoft Excel, they decreased the number of targets to 10 and UAVs to one so that they could solve for the exact solution. This enabled the authors to measure the relative value of their heuristic methods. The exact solution for route planning now has one UAV and 10 targets, which also means 1,036 constraints and 110 decision variables. In the second part of the model development, the algorithms were then applied to 100 randomly created instances of the smaller-sized problem, and the solutions compared to the optimal solution to assess the quality of the algorithms.

Chapter II includes a general background on UAVs, their characteristics, mission types, and usages in war. This part of the thesis provides a general background on the study’s war scenario. Chapter III gives a literature review of the Vehicle Routing Problem (VRP), Traveling Salesman Problem (TSP), and

Orienteering Problem (OP). In this chapter, the problem data and the assumptions are also given in order to define the framework of the study. In Chapter IV the model, the solution, and solution approaches are presented. In Chapter V, recommendations for implementation and possible future research opportunities are discussed.

A. PROBLEM BACKGROUND

In today's information driven world, as compared with the previous two decades, the nature of security has changed completely. New threat perceptions and rapid technological development bring a new doctrine called "preventive war." This doctrine of self defense has been extended to include the right to preemptive strikes if a significant and definite threat is going to occur (National Security Strategy, 2002, p. 15).

For its part, the military should have high Intelligence, Surveillance, and Reconnaissance (ISR) capabilities to fit in this strategy. The doctrine orders armed forces to locate, surveil, discern, and track the suspicious targets. All these missions are conducted to get reliable intelligence in real time. ISR collection is the critical factor in achieving the Joint Vision 2020 Operational Concept of Precision Engagement, which also enhances the ability of joint forces to locate, surveil, discern, and track objectives or targets (Shelton, 2005, p. 22).

Consequently, it is more and more important to gather relevant information in order to assess the threat, separate hostile fighters from peaceful populations, and identify killing devices closely hidden among everyday activities. An unmanned aerial vehicle (UAV) is an unpiloted aircraft that is mostly used for such missions. The three D's could characterize the missions of a UAV: Dull, Dirty and Dangerous. The unmanned nature of the concept presupposes that "the man" is the limiting factor in the success of certain missions. Removing the pilot from the vehicle minimizes human requirements and maximizes the success rate for those three D missions. Moreover, a rough comparison of UAVs and manned aircraft's peacetime costs show that UAVs require dramatically less money and training with no crew risk.

UAVs can be remotely flown by a pilot at a ground control station, or can fly autonomously based on pre-programmed flight plans or more complex collision avoidance systems. Currently, UAVs are used for a number of military missions, including reconnaissance and attack roles and, as a key component of today's ISR missions, are widely accepted as the most effective high-technology weapons system that offers endless surveillance capabilities and can even be used as attack aircraft.

Due to the facts stated above, UAVs play an important role in today's wars, which require Network Centric Warfare (NCW) and Network Enabled Capability (NEC). These concepts are very popular in both the United States and Europe, and dictate that UAVs will increase their importance in the next decades (Wilson, 2007).

Moreover, the development of Unmanned Combat Aerial Vehicles (UCAVs) is increasingly seen as vital to the future of combat aerospace industrial capabilities in the world. This increasing importance of UAVs raises a question of efficient usage. If you have such a key element in your armed forces, it's worth your effort to identify the best ways to utilize the limited resources. So, should this recently developed technology be used efficiently? Do war strategies support the UAV concept? In other words, is this new concept being used well enough, or is any constraint of usage not allowing for success?

The operational performance desired for autonomous vehicles on the battlefield is determined by many variables. Good planning is the most critical factor among all these variables, and can eliminate some of the mission failures. Having trustworthy intelligence of known or suspected enemy locations and mission areas and selecting the right flight path are musts for efficiency. Determining the purpose of the mission clearly, balancing targets and threats, and balancing capabilities and constraints are also important steps of successful mission planning. Mission planners must also consider airspace management conflicts, Joint Suppression of Enemy Air Defenses (JSEAD), Electronic Warfare (EW) and the threat level in the target area, weather conditions of the path, launch and recovery times, and ingress and egress points (Russo, Pedersen, Lethin, & Springer, 2006), but the authors' model can not address all these constraints because of the unpredictable nature of each of these elements.

To summarize, mission planning is the most critical and challenging problem during wartime. Therefore, UAV mission path planning requires algorithm design and computation for the best results due to its complexity. However, it is also known that on the battlefield, due to the urgency of the situation, manual problem solving methods can become necessary. The authors will offer an executable routing model and an algorithm for UAV mission planning for situations when the manual solution approaches are required.

B. PURPOSE OF THE STUDY

In real-time operations it is critical to find, fix, track, target, engage, and assess the opposing forces. Achieving this goal is strictly dependent on having the right intelligence at the right time. Therefore, the armed forces require continuous intelligence and updated data within a reasonably short time after it was collected. If an armed force has a UAV fleet to collect necessary intelligence, and if they complete their mission within a relatively shorter time, they are stronger and have a better chance to survive.

The goal of this study was to develop an optimal route-planning model for UAVs, which are used to get persistent surveillance, tactical and combat reconnaissance with low risk and low cost. This route-planning model will help friendly forces to be time efficient, which is probably the most valuable resource for any army commander during wartime.

For the war scenario in this study, the exact solution needed computerization, but during wartime this way of planning may not be feasible due to resource constraints. Apart from an exact solution, the authors developed three algorithms of heuristic and compared the results of randomly generated scenarios. In this way, they determined the gap between the optimal solution and the heuristic models.

The authors also emphasized the importance of a UAV mission planning method that makes the planner cost efficient and strong. Developing the algorithms, the authors offered the exact solution of the model and provided a literature study of the VRP, TSP, and OP.

C. RESEARCH QUESTIONS

Is it possible to develop an algorithm for having an optimum route planning of identical aerial vehicles from a given depot to mission destinations with different priorities? This research focused on that question. The scenario in this study concerned the route planning of UAVs. Thus, the study’s scope included the UAV concept and characteristics, mission types and usages in wartime. To develop the model, the authors also searched for similar studies and implementations of VRP, TSP, and OP in the literature.

D. RESEARCH SCOPE

This research sought to formulate and solve the UAV route optimization problem. The following areas were included in the research scope:

- Define the UAV concept and mission
- Provide the general information about VRP, TSP, and OP related to the UAV route optimization problem
- Define the assumptions and identify the problem
- Develop appropriate solution methods and algorithms for the best result of heuristic
- Find an exact algorithm
- Compare the results of heuristic relative to the optimal solution
- Give recommendations for further study

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II. UAV ANALYSIS

A. OVERVIEW

While UAVs play an increasing role in a wide variety of mission areas, the extent of their operational impact and importance is just being realized. Hence, the role of UAVs is growing day by day; by itself it could be the subject of an entire project. To explain the logic and basis of this study's model pertaining to the UAV concept, it is necessary to provide a background of UAV technologies, history, characteristics, mission types, and wartime usage. The objective of this review was to develop a basic knowledge and background about UAVs. This general review helped to form the implementation scenario of the model.

B. UAV

The nature of war and intelligence requires updated data and the advantages of high technology. The UAV is one of the most unique technological developments in the history of man's attempt to gain tactical and psychological advantage over his enemies. A chronological history of the UAV and expected future developments will help provide a better understanding of the UAV and its use.

1. History

In 2000, the 106th Congress reported that the goal of the Armed Forces was "to have one-third of the operational deep strike aircraft unmanned and remotely controlled by 2010; and by 2015, one-third of the operational ground combat vehicles be unmanned" (National Defense Authorization Act, 2001). When the use of balloons in war began in America in 1861 by the Union army during the Civil War *(Aerial* Bombers, n.d.), who could guess that could happen?

All of the balloons used in the American Civil War were for reconnaissance, and the hard truth was that men envisioning air surveillance were considered crackpots in those days, not progressive forward thinkers ahead of their time.

Before the American Civil War, on August 22, 1849, the Austrians launched 200 unmanned balloons loaded with explosives against the city of Venice. Some of the bombs exploded as planned but others were carried by the wind and drifted back over the Austrian lines. This is widely accepted as the first recorded action of its type (*Remote piloted aerial vehicles*, 2008).

With these two primitive attempts, the application of air power started decades before the first manned airplane flight on December 17, 1903. UAVs represent one branch of that continuing evolution.

In 1917, Dr. Peter Cooper and Elmer A. Sperry developed an automatic gyroscopic stabilizer to keep an aircraft flying straight and level. This was used on a U.S. Navy Curtiss N-9 trainer aircraft and accepted as the first radio-controlled UAV. The Sperry Aerial Torpedo flew 50 miles carrying a 300-pound bomb in several test flights, but it never saw combat (*Sperry aerial torpedo*, 2008).

Figure 1. Sperry Aerial Torpedo, 1918 (From: Curtiss/Sperry aerial torpedo*, 2001)*

The Queen Bee was the first radio-controlled, returnable and reusable UAV and could fly as high as 17,000 feet, with a range of 300 miles at over 100 mph. The British used Queen Bees as target drones in the Royal Air Force and the Royal Navy between the years 1935 and 1947.

During World War II, Nazi Germany's innovative V-1 (The Revenge Weapon 1), an unmanned flying bomb, was used against nonmilitary targets. It could reach the speed of almost 500 mph, carry 2,000 pounds of explosives, and travel 150 miles before delivering its ordnance (*A brief history of UAVs*, 2008). America's attempts to eliminate the V-1 laid the groundwork for post-war UAV programs in the U.S. At the close of World War II, a company was contracted to develop test missiles with landing gear, which would help save costs. This was the beginning of today's UAV.

Figure 2. German V-1, known as the "doodlebug" or "buzz bomb" (From: The Internet encyclopedia of science-V-1*, n.d.)*

In 1944, the U.S. Navy used PB4Y-1 Liberators and B-17s to carry 25,000 pounds of explosives and flew them by remote control (using television guidance systems) against German V-1s. This was the first time in history a UAV was used against another UAV.

In the 1960s and 70s, the U.S. started its first stealth aircraft program, and not much later developed the AQM-34 Ryan Firebee, a UAV launched and controlled from a host plane and flown for reconnaissance missions.

Figure 3. DC-130H Hercules drone control with a pair of AQM-34 Firebee (From: Wikimedia Commons, 2008)

In the late 1970s and 80s Israel, an aggressive UAV developer, started using the Scout and the Pioneer - lighter, smaller, inexpensive UAV models, with 360-degree, real-time, surveillance data transmitting capabilities - which are still in use today.

Figure 4. The start of modern UAV Era: "the Scout" (From: Israeli weapons, n.d.) and "the Pioneer" (From: Spies that fly, n.d.)

Although UAV technology developed dramatically throughout the 20th century, UAVs earned a permanent place in the arsenal with the advent of the Predator drone. Predators flew in the skies over the Balkans, Afghanistan, and Middle East, with a range of 450 NM, and provided 14-16 hours of surveillance via high definition color television, infrared cameras, and Synthetic Aperture Radar (SAR) before returning to its base. A ground team from a remote control station controls the plane, either by a line-of-sight radio connection or via a satellite link. Though the Predator was designed purely for reconnaissance use, some of the current versions are loaded with Hellfire missiles for attack purposes.

Figure 5. UAV Predator (From: Spies that fly, n.d.)

2. Future Projects

According to Dyke Weatherington, deputy of the Defense UAV Office, some UAVs under development will be as small as our hand; in the future, it may be that a small UAV could fly into the window of a building, land at some innocuous location and observe activities (Garamone, 2002). Not surprisingly, his speech explains the situation that now exists. It is obvious that only human imagination can limit UAV usage and development.

The tactical UAV called Shadow 200 supports that claim. It is used to locate, recognize and identify targets up to 125 km from a brigade tactical operations centre. This air vehicle is of composite structure and its compact size and small engine produce very low radar, which makes it difficult to detect.

Figure 6. RQ-7 Shadow UAV (From: Defense Industry Daily, n.d.)

A newly developed Marine UAV, called Dragon Eye, gives small-unit leaders the opportunity to explore the hidden parts of the battlefield. The “over the hill” surveillance capability of this small hand-launched UAV is so close to the cutting edge of science that it might have been built by the aliens that inhabit Hollywood movies.

Another little-known development of NASA and the U.S. Department of Defense is the miniature jet fighter X-36. It is remotely piloted from the ground using a TV camera in the cockpit to keep the operator informed, and vectored by exhaust for maneuverability. It is expected to fly by remote control and be operated by pilots who, as children, are the game experts of today.

The Black Widow, which has a six-inch wingspan and weighs only two ounces, has been developed for military surveillance, law enforcement, and civilian rescue efforts. Micro UAVs offer flexible flight characteristics for changing mission requirements and are expected to be a good solution for rapid and urgent reconnaissance needs.

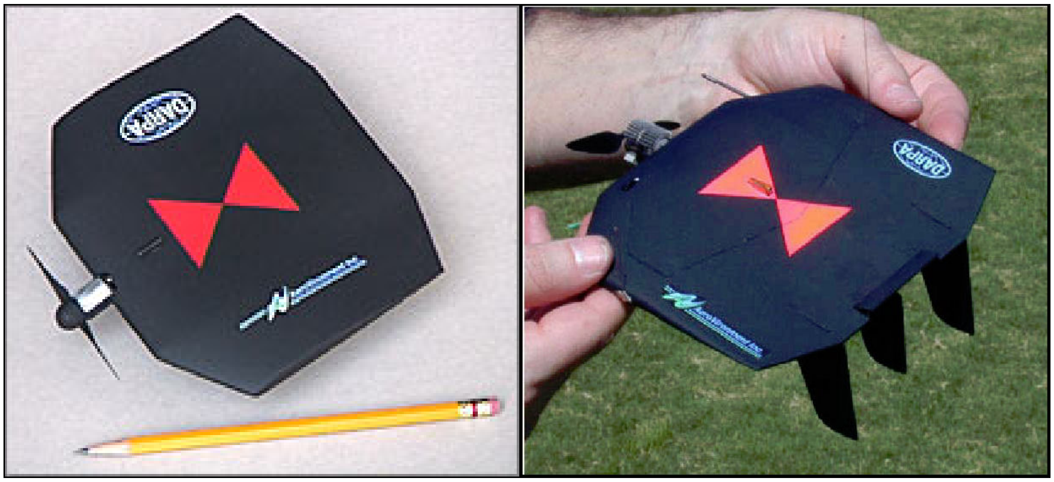

Figure 7. Black Widow, AeroVironment's award-winning Micro UAV (From: Black Widow, 2006)

The next generation of UAVs will be smaller, lighter, inexpensive, easier to train and more complicated than existing UAVs. Also, in the foreseeable future, we will be able to use UAVs to detect nuclear, biological and chemical weapons, to find the survivors of an earthquake and to provide relatively cheap and reliable communication and data transfer across the battlefield.

In the near future, UAVs are expected to play an important role in commercial applications. Large high-tech companies are already looking forward to using UAVs in operations. For now, the Federal Aviation Administration (FAA) restricts the use of UAVs in commercial applications, but is expected to make some changes in its regulations in the near future which could allow UAVs to be widely deployed for business uses.

Although there are strict FAA restrictions on their use, UAVs are already allowed for some civilian use. For example, the agricultural industry uses UAVs to spray fertilizer and pesticide over large fields or to monitor the crops. Other current commercial uses include mineral exploration, unexploded ordnance detection/disposal, coast watch, telecommunications, air traffic control, and ground traffic control.

3. UAV Mission Types

The term UAV refers to a wide range of technological innovations. The FAA has changed the UAV acronym to UAS (Unmanned Aircraft System) to reflect the fact that the vehicles operate with the help of ground stations and other elements.

To better understand the UAV concept and determine the data used in the model, a classification of UAVs is needed. To work toward a classification, an understanding of the uses of UAVs is required. The start of the innovation and the primary use of UAVs were grounded on the need for intelligence about opposing forces. In addition, they have been used as decoys for aircraft or for the suppression of enemy air defense. Also, it is known that they are planned for use as jet fighters in dogfights of the near future.

The characteristics of the mission determine the design of the UAV. For example, a combat UAV is required to carry bombs and be fast and agile, while an ordinary intelligence UAV is designed to have long endurance time. As a result, the combat UAV’s endurance time is almost 2-4 hours while the ISR UAVs endurance time is more than 20 hours. Combat UAVs are mostly as big as a fighter aircraft while a low-altitude ISR UAV weights less than thirty kilograms. Therefore, it is necessary to understand the five basic types of UAV missions:

- Target and decoy
- Intelligence, Surveillance, and Reconnaissance (ISR)
- Combat
- Research and development
- Civil and Commercial UAVs

Target and decoy UAVs provide a target that simulates an enemy aircraft or missile. The data transmitted through data uplinks to the targetUAV allows for simulation of real-time war. Integration attempts to provide attack capability to a UAV for high-risk missions is called UAV Combat mission.

The scenario in this thesis included the need for intelligence to properly plan ISR missions. The model also included two different types of ISR missions represented with different times required to complete the mission. The next two sections provides a general overview of ISR and present information on one special type of ISR mission called Battle Damage Assessment.

a. Intelligence, Surveillance, and Reconnaissance (ISR) Missions

The Department of Defense defines intelligence as “information and knowledge obtained through observation, investigation, analysis, or understanding” (Department of Defense, 2001, p. 214). Surveillance and reconnaissance refers to the way the information is observed. Surveillance is observation to get whatever data is available and reconnaissance is a specific mission embarked upon to collect that specific data.

In wartime, it is critical to find, fix, track, target, engage, and assess the opposing forces. ISR UAVs supply armed forces intelligence requirements. ISR capabilities dramatically increase situational awareness on those critical decision steps.

For instance J. M. Fyfe’s research pointed out that although some newly developed moving target indicators flew over Baghdad as a traditional way of ISR, Global Hawk UAV maintained the best ISR coverage during Operation Iraqi Freedom (Fyfe, 2005).

b. Battle Damage Assessment (BDA) Missions

Confirming a target and verifying its destruction, known as Battle Damage Assessment (BDA), is also an ISR activity. For these two missions (ISR and BDA) where high-resolution pictures are necessary to decide, recognize, and classify the targets, UAVs should fly at relatively low altitudes to provide adequate imagery.

BDA is the practice of assessing damage inflicted on a target by an air campaign. Operational Commanders must decide whether or not to strike and hit the targets based on BDA images. BDA is part of the larger discipline of Combat Assessment (CA), also referred to as Bomb Damage Assessment (BA). Assessment is performed using many techniques including in-weapon cameras, gun cameras, forces on the ground near the target, and follow-up visits to the target (Rauch, 2004).

In general, ISR is conducted to provide intelligence information to decision makers at all levels of command to give them the fullest possible understanding of the adversary (Air Force Doctrine Document 2-5.2, p. 3), while BDA provides the information for a specific level in the chain of command. ISR missions generally take more time to accomplish than BDA missions. In UAV terminology, “target mission complete” means essentially that the pictures or the video records of the target have been taken while making orbits over the mission area, and the raw images have been transmitted to the base successfully so they can be assessed by the decision makers.

4. UAV Equipment Classification

UAV equipment has very specific constraints like power, cost, and weight. Design of the UAV is a series of trade-offs among those constraints. To choose or develop the right UAV type for the mission is an optimization problem. Flight endurance time, mission altitude, range, and the weight of the asset have decisive influence on classification of the UAV. For a widely accepted UAV classification chart, see Table 1.

Table 1. Suggested UAV Equipment Type classifications (From: Janes Defense Magazine, 2007)

UAV categories [1]	Acronym	Range (km)	Altitude (m)	Endurance (h)	T-O mass (kg)
Micro (6.4)	µ	<10	250	1	<5
Miniature (28.1)	Mini	<10	150_[3] to 300_[2]	<2	<30 (150_[3])
Close range (14.4)	CR	10 to 30	3000	2 to 4	150
Short range (13.8)	SR	30 to 70	3000	3 to 6	200
Medium range (20.4)	MR	70 to 200	5000	6 to 10	1250
Medium range endurance (3.2)	MRE	>500	8000	10 to 18	1250
Low-altitude deep penetration (1.5)	LADP	>250	50 to 9000	.5 to 1	350
Low-altitude long endurance [4] (0.5)	LALE	>500	3000	>24	<30
Medium-altitude long endurance (3.8)	MALE	>500	14000	24 to 48	1500
High-altitude long endurance (4.5)	HALE	>2000	20000	24 to 48	12000
Special purpose UAVs					
Unmanned Combat Aerial Vehicle (2.7)	UCAV	±1,500	10000	±2	10000
Lethal	LETH	300	4000	3 to 4	250
Decoy	DEC	0 to 500	5000	<4	250
Stratospheric (0.4)	STRATO	>2000	20000 to 30000	>48	TBD
Exo-Stratospheric (0.4)	EXO	TBD	>30000	TBD	TBD

Notes:

1. Estimated percentage of overall market at mid-2007 based on 784-type sample
2. According to National Legislation
3. In Japan
4. Aerosonde, ScanEagle, SeaScan, and Silver Fox

Although there are two classifications presented so far, each of them is used for different purposes. Mission types of UAVs do not necessarily match with a certain equipment type of UAV. The decision makers must assess the current situation and assign the most convenient type of UAV equipment for every specific mission. The air defense umbrella of the opposing forces, the distance of the friendly forces to the operation area, or the radar sensitivity threshold of the opposing forces may require different UAV equipment for the same mission.

Knowing the missions types for UAVs helped the authors to decide which particular missions to focus on. Since intelligence about opposing forces was needed, their UAVs would fly ISR missions. As they searched for more information about ISR missions, the authors realized that BDA is a subcategory of ISR missions and that they should also include this mission type in our study. While a regular ISR mission finds, tracks, and targets the opposing forces, BDA missions concentrate on a specific target and record high-resolution images of it. So, for this thesis it was decided to have two different types of ISR missions with different accomplishment times.

Once the mission types were decided upon, the next step was to choose the most effective equipment to get the mission done. The need for persistent intelligence mandated higher endurance times for the UAVs. Considering that an average Electro-optic (EO), Infrared (IR) and SAR Pod weights 50 lbs., it was not possible to use the micro or miniature UAVs. However, a fast or agile fighter UAV was not needed, either. Regarding the weight, endurance time and range constraints, there were only two UAV types left to choose for the missions. These UAV types were Medium Altitude Long Endurance (MALE) UAVs and High Altitude Long Endurance (HALE) UAVs. Since both UAV types have the same endurance time on average the authors did not have a preference between these two. Meanwhile, it was decided that the UAVs would have 20 hours of endurance time and complete two different types of ISR missions for the scenario.

5. UAV Assumptions to Implement the Scenario

The scenario that was modeled in this study dealt with Reconnaissance and BDA missions, so the characteristics of an appropriate UAV type were used. As discussed above, MALE and HALE UAVs seemed to be the most appropriate UAV types for the scenario. They would meet the mission requirements and provide persistent intelligence with their high endurance times. By choosing these UAVs, the UAVs would be able to visit more than one target on each sortie; this gives rise to the problem of effective route planning.

The average endurance time of the HALE and MALE UAVs, which are ISR and BDA focused, is 24 hours. The model assumed that the UAV endurance time would be 20 hours per flight. No set-up time or delay was taken into consideration. The flight time would start when the UAV took off and end when it returned to base. A UAV could complete an endless number of missions, one after another, as long as the endurance time of the unit permitted it, but for every sortie it would have a time limit of 20 hours. Unused times of the flight could not be carried over to the next flight.

The nature of intelligence and war requires continually updated data. As long as there are UAVs, there will always be new intelligence requirements to gain a better situational awareness about the opposing forces, since decision makers always ask for more information. There are always more missions than the UAVs can complete. Consequently, the limiting factor would be the number of UAVs. Therefore, performing all missions is not a requirement (constraint) in the model. UAVs are known as High Valued Air Assets (HVAA) during military operations. Since UAVs are force multipliers, the efficient usage of UAVs would highly affect military power. Operational fleets of UAVs usually consist of three assets. The model supposed a force of three High Altitude Long Endurance (HALE) UAVs on a 400 Nautical Miles (NM) x 400 NM two-dimensional plane.

The HALE UAVs were expected to fly well above the jet stream and other high velocity currents, averaging 40–80 knots in speed, with peaks of up to 160 knots (Defense Update Magazine, 2007). To keep the calculations and the model simple, it was stipulated that UAVs have a constant speed of 50 NM per hour. Using a constant speed helps to convert the distances to time bases with a simple calculation of dividing the distance by 50, the constant speed. Take off and landing times of UAV and the relatively low speeds of taking off and landing were neglected.

After determining the UAV type, number, endurance time, and speed, the authors needed to create a specific wartime scenario to model. As stated previously, since there is a continuous need for intelligence during war and UAVs are expensive, high-tech force multipliers, it is expected that the number of missions will always exceed the capacity of the UAVs. Hence, route-planning applications increase in importance and so does this model.

In real life, the Air Tasking Order (ATO) of the day shows the missions to be accomplished for the Air Force. The ATO also contains assignments and associated time requirements for the various subunits to integrate the joint operations and allow them to function with greater harmony. For this model, Microsoft Excel randomly generated the coordinates of 20 targets (excluding the base) for the next day. The “target” here is defined as the generated geographical location of a mission with assigned bonus points representing the priority of the mission. In wartime, targets for ISR UAVs may be headquarters or defense formations of opposing forces, or possibly a bridge. Since the number of possible solutions increases exponentially when the number of targets is increased and, in a real instance, it is likely that a fleet of three UAVs will have less than 20 targets to be routed at any given time, it was decided to have 20 targets. For number of targets less then 20, the heuristic methods are easier to apply, but the authors wanted to be sure that the algorithms could handle all realistic numbers of targets.

The ATO also defines the mission requirements, or at least the mission type. As stated previously, this research project uses two types of UAV missions: BDA and ISR. To adapt the situation to the model, the authors supposed that ISR missions would take three hours to accomplish while BDA missions would take two hours. These times for the missions are the duration that a UAV must fly and orbit over the target to complete the mission for that target. Microsoft Excel was used to randomly assign each target either a two-hour or three-hour target time, thereby representing both types of missions.

Having three UAVs and two different mission types on a two-dimensional plane with 20 targets, the next problem became providing priorities to the missions. In wartime it is expected to have vital missions as well as ordinary ones. Some urgent missions may make more contribution to operations than others. Each target was assigned bonus points relative to the mission’s priority to represent the importance level of the mission. Bonus points for the missions were generated randomly.

In summary, three UAV routes with a 20-hour maximum flight time and constant speed were planned for 20 randomly generated targets on a 400 NM x 400 NM plane with the base located in the center of the plane. Each of the 20 targets were given a mission time of either two hours or three hours, and each was assigned a different bonus point value representing its priority. The goal was to maximize the sum of all bonus points collected.

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III. LITERATURE REVIEW

This chapter provides a general literature summary of the Vehicle Routing Problem (VRP), the Traveling Salesman Problem (TSP), the Orienteering Problem (OP) and the Prize Collecting TSP in the context of this study's model and solution algorithms. This literature review's goal is to develop a basic knowledge about the problem and possible approaches to solve it. In this chapter, the scenario assumptions will also be described to define the framework of the study.

Before starting to develop a model to address the study problem, the authors reviewed the current literature to answer the questions: has anyone proposed a similar problem? If yes, how can the solution be adapted to this study's situation? Similar studies of the problem led the authors to research the Traveling Salesman Problem (TSP) first.

A. TRAVELING SALESMAN PROBLEM

The TSP was first described in the 1800s as the problem of the "Hamiltonian Circuit" by Sir William Rowan Hamilton. The problem was whether a directed graph has a circuit which passes exactly once through every node. This question starts with a basic model of the Minimum Traveling Salesman Problem (MTSP) (Applegate, Bixby, Chvatal, & Cook, 2006, p. 101). A discussion of the early work of Hamilton and the British mathematician Thomas Kirkman can be found in the book Graph Theory (1736-1936) (Biggs, Lloyd, & Wilson, 1976).

No actual answer or study is found until Karl Menger introduced the TSP under the name of "Botenproblem" (Messenger Problem) in 1930 at a mathematical colloquium in Vienna. (Menger, 1932) His theory looked for the shortest path for postmen and up to that time the best solution was to always send the salesman to the next closest city (Laporte, 2006).

In 1954 George Dantzig, Ray Fulkerson, and Selmer Johnson applied the simplex method to solve the TSP with linear programming. (Dantzig, Fulkerson, and Johnson, 1954). They illustrated the power of their method by showing the shortest way of combining 49 cities. Finding a solution for such a big number was an impressive job at that time (*Traveling Salesman Problem history*, 2005). Later, in 1957, L. L. Barachet published a graphical solution for a small number of cities, to be used manually (Barachet, 1957). It gave more optimal solutions for groups of cities numbering around 10.

The development of computer technology made it easier to solve the problem at greater levels of complexity. In the 1960s, for example, R. Bellman described the first solution with dynamic programming on an IBM 650 computer. (Bellman, 1960).

Just after Miller reported Gomory's cutting-plane algorithm (Miller *et al.*, 1960), M. F. Dacey developed a heuristic algorithm, which is only 4.8% less effective than the optimal solution, which is an impressive result (Dacey, 1960). The branch-and-bound algorithm, developed by Little et al. (1963), proved to be successful for a set of 30-city asymmetric TSPs.

In 1970, Held and Karp introduced the 1-tree relaxation method of the TSP (Held, Karp, 1970). He used node weights to improve the bound given by the optimal 1-tree. Development of solution methods reached a milestone with Crowder and Padbergs' (1980) solution of a 318-city set, which remained the largest TSP solved until 1987. Padberg and Rinaldi (1987) solved a 532-city problem using the so-called branch and cut method.

Naturally, the exact solution of a TSP can be reached in time O(n!) by enumerating all tours, but this is very impractical for growing numbers. For a problem of 5 nodes, you will have O(5!) = 120 routes to enumerate. If the solution time is less critical than the solution quality, then it is acceptable to try all permutations to find the best way. But what if you have 10 nodes, and therefore 3,628,800 possible routes? Will you spend your days to try?

Since the TSP is one of the NP-complete problems, the method called Dynamic Programming stands as the second best approach to this kind of problem. The term "Dynamic Programming" refers to the method of finding optimal solutions to a large problem by solving several smaller problems and keeping track of those smaller solutions, usually in order to reuse them. This method gives an algorithm of complexity $O(n^2 \times 2^n)$ routes, exponential but faster than O(n!). (Applegate, Bixby, Chvatal, & Cook, 2006, p. 101).

Other recommended approaches are branch-and-bound algorithms for problems up to 40-60 nodes (Volgenant and Jonker 1982), and linear programming algorithms for problemsup to 200 nodes (Grötschel, 1980). The well known “branch-and-bound” search method splits the space into two or more subsets in an attempt to create sub-problems that may be easier to solve than the original. For example, suppose that a tour group plans to travel through the cities of the U.S. It should first be determined whether or not the group should travel directly between Philadelphia and New York; the set of all tours can then be split into those that use this route and those that do not.

Implementation of branch-and-bound and problem-specific cut generation method holds the current record of solving an instance with 85,900 cities. (Applegate, Bixby, Chvatal, & Cook, 2006). The studies of the 1990s focused on applications such as vehicle routing, parts manufacturing and assembly, electronic board manufacturing, space exploration, oil exploration, production job scheduling.

Fundamentally, the basic TSP is this: given a number of cities and the costs of traveling from any city to any other city, what is the least-costly round-trip route that visits each city exactly once and then returns to the starting city. The goal with the UAV scenario of this study is not necessarily finding the shortest path, but maximizing the collected bonuses from each of the destination points, since every point cannot be visited due to constraints.

B. VEHICLE ROUTING PROBLEM

Most routing and scheduling problems faced by any industry are different forms of VRP. The VRP is a combinatorial optimization and NP-Hard problem seeking to visit a number of points (customers, retailers, etc.) with a fleet of vehicles. The objective function of the VRP is to minimize the travel distance or minimize the number of vehicles required to service all of the points. The objective function is subject to the constraints that each customer is serviced exactly once and each route starts and ends at the beginning point or depot. Capacity restrictions of the vehicles, demands of the customers, and distance or time restrictions of vehicles may apply due to the scenario requirements. The number of depots or vehicles and the priority of customers are also important considerations in the problem.

Several variations and specializations of the vehicle routing problem exist in the literature. The main VRP types are:

- Capacitated VRP (CVRP): Every vehicle has a limited capacity
- VRP with time windows (VRPTW): Every customer has to be supplied within a certain time window
- Multiple Depot (MDVRP) VRP: The vendor uses many depots to supply the customers
- VRP with Pick-Up and Delivering (VRPPD): Customers may return some goods to the depot
- Split Delivery VRP (SDVRP): Customers may be served by more than one vehicle
- Stochastic VRP (SVRP): Some values (like number of customers, their demands, serve time, or travel time) are random
- Periodic VRP (PVRP): The deliveries may be done in some days

Fundamentally, the problem of this study is different from all of the problem types given above. So, it cannot be classified as any one of the Vehicle Routing problem types given above.

Due to the complexity of this research problem, most of the algorithms that solve the VRP are heuristic in nature. The term heuristic is used for algorithms that find a solution from all possible solutions, but do not guarantee that the solution found is the best. For that reason, heuristic algorithms may be considered as approximate but not exact algorithms. This method generally finds a solution close to optimal solution in a relatively shorter time. Sometimes, heuristics may be the best possible solution. But the algorithm is still called a heuristic until the solution is proven to be the best. A metaheuristic is a heuristic method for solving a very general class of computational problems by combining given procedures in an efficient way. The name metaheuristic is a combined form of the Greek prefix "meta" (beyond) and word "heuristic" (to find). Metaheuristics are generally applied to problems for which there is no satisfactory solution method or when it is not practical to implement such a method. A metaheuristic method is mostly used to solve combinatorial optimization problems.

However, optimization heuristics are likely to perform very poorly as the problem size grows. Because of this a variety of approximation algorithms or heuristics are executed to find a solution. In particular, when solution time is more critical than solution quality, heuristics are recommended. The Parallel Savings Algorithm (Clarke and Wright, 1964), the Sweep Algorithm (Gillett and Miller, 1974), the Push-Forward-Insertion method (Solomon, 1987; Thangiah et al., 1993), and the Nearest Neighborhood Search (Rosenkratz, Stearns and Lewis, 1977; Solomon, 1987; Fisher, 1994) are the most commonly used and best heuristics that have been developed so far (Johnson & McGeoch, 2002, pp. 369-443).

The Parallel Savings Algorithm applies to problems for which the number of vehicles is not fixed (it is a decision variable), and works equally well for both directed and undirected problems (Clarke & Wright, 1964, pp. 568–581). The basic method of this algorithm is to generate distance savings by merging two routes into a single route. This aforementioned algorithm does not work for this case study, because this study has a fixed number of UAVs.

In the Sweep Algorithm, a random demand point is chosen as the starting point. Other customers are ordered based on the angle made between them, the depot, and the starting point. So, the customers are served or “swept” in a clockwise direction. Thus, each vehicle gets an efficient route (Simchi-Levi, Chen, & Bramel, 2004, pp. 231-233). Since it is not known whether it is feasible in Microsoft Excel to generate random selections of targets and to route them clockwise, the authors did not attempt this heuristic method for their problem.

The Push-Forward-Insertion Algorithm computes the cost of inserting a new customer into the route (Chambers, 1998, p. 352). The authors’ value-based heuristic method was inspired by this algorithm, although they look at appending nodes to the route rather than inserting nodes between other nodes. Their heuristic, which is provided in Chapter III, calculated the bonus per distance values for all the next possible targets and appended the target with the highest value.

In the Nearest Neighborhood Search, the traveler always goes to the next nearest and unvisited point. This heuristic is also one of the heuristics used in this study’s model. The results and the conclusions of the model and the three solution heuristics developed will be provided in the following chapters.

C. ORIENTEERING PROBLEM AND PRIZE COLLECTING TSP

Given a set **P** of *n* points in the plane, a starting point *r* € **P**, and a length constraint b, one needs to find a tour starting at r that visits as many points of P as possible and of length not exceeding b. This is called the Orienteering Problem, which is another variant of the Prize Collecting TSP. The OP is also called the Selective Traveling Salesman Problem (STSP) (Archetti, Feillet, Hertz, & Speranza, 2007). The objective is to minimize total travel cost and the net penalties for failing to visit some points, while visiting enough points to collect a prescribed amount of prize money.

TSPs with profits (prizes) are encountered in many different situations. A historical application of TSP with profits is orienteering events, introduced by Tsiligirides (1984). In orienteering competition players start from a control point and have to reach another control point within a time limit. Meantime, they can visit other control points and collect scores. The competitor ending with the maximum score wins the competition. The problem of finding the optimal route is an OP. Golden et al. (1984) propose applying the same modeling to a VRP with capacity constraints. A fleet of trucks must periodically deliver fuel to a number of customers. In this problem, a customer's fuel level must be kept above a minimum level at all points in time. A first step of the solution procedure is to determine which customers to serve each day. A forecasted tank level for each customer results in a measure of emergency for each customer. Another historical application of TSPs with profits is the scheduling of daily operations of a steel rolling mill, as introduced by Balas and Martin (1985), (1989). This paper gives rise to a PCTSP with penalty terms in the objective function.

There has been work on exact methods for the OP such as integer programming, dynamic programming, and branch-and-cut algorithms. Although these approaches have yielded solutions to smaller sized problems, as in other NP-hard problems, the computational limitations of exact algorithms encourage the exploration of heuristic procedures. Here are the solution methods presented in the major studies on this subject:

1. Heuristic Methods

- “Greedy Insertion” by Tsiligirides (1984)
- “Sweep Based Insertion” by Tsiligirides (1984)
- “Greedy Insertion, Path Improvement” by Golden et al. (1987)
- “Random Insertion, Path Improvement” by Keller (1989)

2. Meta Heuristic Methods

- “Neural Network” by Wang et al. (1995)
- “Genetic Algorithm” by Tasgetiren and Smith (2000)
- ”Ant Colony” by Liang et al. (2001)
- “Tabu Search” by Liang et al. (2001)

3. Exact Methods

- “Dynamic Programming” by Hayes and Norman (1984)
- “Branch and Bound” by Kataoka and Morito (1988)
- “0-1 integer Programming” by Leifer and Rosenwein (1993)
- “Branch and Cut” by Fishetti et al. (1998)

In the general form mentioned above the PCTSP was first formulated by Balas. His problem arose during the task of developing daily schedules for a steel rolling mill. The only results on guaranteed heuristics for the Prize Collecting TSP are due to Awerbuch et al 8. While some of the TSPs with profits have been investigated by a number of researchers, there are only a few papers available in the literature about TSPs with profits that consider the case of multiple tours. Since this study’s problem requires multiple tours, one for each UAV, it will consider the extension of the Orienteering Problem to the case of multiple tours, known as the Team Orienteering Problem (TOP). In the TOP, there is a time constraint on each tour The TOP first appeared in the literature in a paper by Butt and Cavalier (1994, pp. 101-111) under the name Multiple Tour Maximum Collection Problem (MTMCP), while the definition of TOP was introduced by Chao, Golden, and Wasil (1996, pp. 464-474). Two recent papers by Tang and Miller-Hooks (2005) and Archetti, Hertz, and Speranza (2006) proposed metaheuristics for the solution of the TOP, but the exact difference between MTMCP and TOP is not defined by these papers.

IV. MODEL AND SOLUTION

This chapter the authors present the algorithms they developed to solve problems that are too large to solve to optimality in Microsoft Excel. Introducing the decision variables, objective function, and constraints will provide a better understanding of the model. First, the authors developed and applied three heuristic methods to the case of three UAVs and 20 targets. In this way, the heuristic methods could be compared to each other. However, the quality of the heuristics relative to optimality could not be determined in this way. To set a measurement criterion, the authors solved the problem with one UAV and 10 targets to find the exact solution. After finding the exact solution for this situation, the authors applied their heuristics to the same set of generated targets. They did this for 100 randomly generated instances and determined the gap between the optimal solution and their heuristic solutions. In this way, they evaluated and compared their three heuristic methods. To develop the 100 randomly generated instances, the authors used Microsoft Excel to generate random locations and bonus points of the targets.

A. MODEL DEVELOPMENT

The authors formulated their problem in the following manner:

1. Decision Variables and Parameters

n: number of targets (Depot is the 1st target)

m: number of UAVs

c_j = bonus value for target j, for j =1, 2, …, n (Depot bonus value=0)

E = endurance time

t_{ij} = time spent to go from target i to target j and complete the mission on target j

x_{ijk} = 1 if UAV k goes from target i to target j; = 0 otherwise

2. Objective function

Maximize

$$\sum_{i=1}^{n} \sum_{j=1}^{n} \sum_{k=1}^{m} c_j x_{ijk}$$

3. Constraints

Endurance constraint:

$$\sum_{i=1}^{n} \sum_{j=1}^{n} t_{ij} x_{ijk} \leq E \qquad k=1,2,\ldots m \tag{1}$$

Leave target once or not:

$$\sum_{j=1}^{n} \sum_{k=1}^{m} x_{ijk} \leq 1 \qquad i=1,2,\ldots n \tag{2}$$

Balance:

$$\sum_{i=1}^{n} \sum_{k=1}^{m} x_{ijk} - \sum_{i=1}^{n} \sum_{k=1}^{m} x_{jik} = 0 \qquad j=1,2,\ldots n \tag{3}$$

Start at depot:

$$\sum_{j=1}^{n} x_{1jk} = 1 \qquad k=1,2,\ldots m \tag{4}$$

Sub-tour elimination:

$$\sum_{i \in S} \sum_{j \in S} x_{ijk} \leq |S| - 1 \text{, for all } S \subseteq \{2, \ldots, n\} \quad k=1,2,\ldots m \tag{5}$$

Binary variables:

$$x_{ijk} \in \{0, 1\} \tag{6}$$

The objective function was to maximize the total bonus points collected with all three UAVs. Constraint (1) ensured that for each UAV, total time should be less than the endurance time. Total time is the sum of all travel time and all service time spent for visited targets. Constraint (2) ensured that the UAV could leave target once if necessary. Constraint (3) was the balance constraint, which ensured that if a UAV arrived at a target it would leave that target. If a UAV did not arrive at a target it could not leave that target. The study did not need constraints for arrivals because of the balance constraints. Constraint (4) ensured that each UAV started its route from the depot. Constraints (3) and (4) together ensured that each UAV returned to the depot. Constraint (6) is the usual sub-tour elimination constraint. It ensured that the route could not form a loop without including the depot. Finally, all decision variables were binary.

For a high number of targets, this is a computationally difficult problem for the solver in Microsoft Excel. Since the number of possible solutions increases exponentially when the number of targets is increased, that authors examined three heuristic methods for quick solution, fully understanding that they may not get the optimum solution every time.

Next, each heuristic was described in detail and used to solve the 100 randomly generated problem instances. There were 20 targets and three UAVs for these instances, for which the heuristics were compared to see how well they did against each other. Subsequently, the exact solution for 10 targets and one UAV was presented. The solution of one UAV and 10 targets determined the gap between the authors' heuristics and the exact solution. The authors applied the exact solution and three heuristics to 100 randomly generated instances and figured out how well their heuristics did compare to the best solution.

B. HEURISTIC METHODS

In the literature, there are several natural heuristic algorithms for MTMCP or OP, and most of them produce good solutions. However in their original form none of them was applicable, to the study case. Since minimizing the travel time to any point below the UAV's endurance time does not make any difference in terms of minimizing the cost, the authors focused on maximizing the collected bonus points at each sortie by developing greedy algorithms. A greedy algorithm is any algorithm that follows the problem solving metaheuristic of making the locally optimum choice at each stage with the hope of finding the global optimum (Cormen, Leiserson, & Rivest, 1990, p. 329).

The authors developed three greedy heuristics. These heuristics are "The Closest," "The Highest Point," and "The Highest Value" algorithms. "The Closest" heuristic method considers distance. "The Highest Point" considers the bonus point values. Different from the first two algorithms, "The Highest Value" is a weighted greedy heuristic considering the bonus points per distance value. The authors' heuristics produced the routing incrementally, choosing the next point at each stage by looking at the targets remaining to be visited.

Randomly located targets were generated to develop different model instances. Then, the heuristics were used to solve and compare the solution results across the heuristics for each scenario. The coordinate of the depot was accepted as (0, 0), at the origin in the center of the plane. The authors also generated random numbers for the bonus points and the service times of the targets. The authors developed algorithms for each heuristic method and programmed the algorithms into Microsoft Excel. The program that ran each of the three heuristics can also be used for any number of targets less than 20. They followed the steps within each algorithm once for each UAV. Before starting step one in any heuristic, the authors did data preprocessing for all algorithms. Using the coordinates of each mission location, they formed a distance chart showing the distances between all targets. They divided each number in the distance chart by the velocity of the UAV in order to form the time chart, which showed the travel times between all targets.

1. “The Closest” Method

The algorithm for this method is as follows:

1) Depot is the initial current point
2) Order all unvisited targets from shortest travel time to longest travel time from current point
3) Go to the target that has the shortest travel time
4) Calculate the available time

   [Available time = Endurance time - (∑Travel time + ∑ service time)]
5) Calculate the required time for each unvisited target

   (Required time = Travel time from current point to the next target + Service time of the next target + Travel time from next target to the depot)
6) If required time of any unvisited target is less than the available time then order all targets with (required time) <= (available time) by travel time and go to step 3, else return to the depot

Table 2 shows the relevant information for the algorithm at step 1. The first column of Table 2 gives a symbolic letter of target name and the second column represents the mission duration time of the target (either two or three hours). The third column shows the bonus points of targets, which are assigned to represent the priority of the mission. Column four shows the travel time needed for a UAV to go from the depot to the related target shown in column one. Column five ranks the targets according to their travel times from the current location of the UAV from longest travel time to shortest travel time and the last column shows the total required time to go to the target, carry out the mission and return to the depot. For example, Target A needs two hours of service time and has nine bonus points. Two hours of travel time are needed to go this target and it is the 19^{th} based on travel times among all 20 targets. This method does not take into consideration the bonus points of the target while putting targets in order. The UAV goes to the target that has the shortest travel time. The required time for each unvisited target is then recalculated. The process continues till available time is greater than any required time. If there is no available target to go, the UAV returns to the depot. The same rules are followed for the other UAVs.

Table 2. An example of "The Closest" method (Putting targets in order when the UAV is at depot)

Column 1	*2*	*3*	*4*	*5*	*6*
	Service Time	**Points**	**Travel Time**	**Rank**	**Required Time**
A	2	9	2.00	19	6.71
B	3	6	4.75	1	11.80
C	3	2	3.24	13	9.61
D	2	2	3.54	10	8.41
E	2	6	4.19	5	10.69
F	2	10	3.35	11	8.13
G	2	6	4.74	2	11.65
H	2	1	4.01	6	10.73
I	2	10	3.11	14	7.52
J	2	6	2.24	17	6.71
K	3	2	3.88	7	11.44
L	2	9	0.71	20	20.00
M	2	2	2.54	16	7.28
N	2	6	3.72	9	9.95
O	3	9	3.82	8	10.05
P	3	3	2.16	18	7.32
R	2	4	2.67	15	8.00
S	2	5	3.35	12	8.62
T	2	7	4.53	3	10.97
U	2	6	4.48	4	10.28

2. "The Highest Point" Method

The algorithm for this method is as below:

1) Depot is the initial current point
2) Order all unvisited targets from highest bonus point value to lowest bonus point value
3) Go to the target that has the highest bonus point value
4) Calculate the available time

   [Available time = Endurance time - (∑Travel time + ∑ service time)]

5) Calculate the required time for each unvisited target

(Required time = Travel time from current point to the next target + Service time of the next target + Travel time from next target to the depot)

6) If required time of any unvisited target is less than the available time then order all targets with (required time) <= (available time) by bonus point value and go to step 3, else return to the depot

Table 3 shows the relevant information for the algorithm at step 1. The first column of Table 3 gives a symbolic letter of target name and the second column represents the mission duration time of the target (either two or three hours). The third column shows the travel time of a UAV to go from the depot to the related target shown in the first column. The fourth column shows the bonus points of targets, which are assigned to represent the priority of the mission. Column five ranks the targets according to their distances from the current location of the UAV and column six shows the required time to go to the target, carry out the mission and return to the depot. This method does not take into consideration the travel times between the targets unless two or more targets have the same bonus point while putting targets in order. The UAV goes to the target that has the highest bonus point. The available and required times are then calculated. The process continues till available time is greater than any required time. If there is no available target to go, the UAV returns to the depot.

Table 3. An example of “The Highest Point” method (Putting targets in order when the UAV is at depot)

1	2	3	4	5	6
	Service Time	**Travel Time**	**Points**	**Rank**	**Required Time**
A	2	2.00	9	16.19	9.11
B	3	4.75	6	9.01	9.39
C	3	3.24	2	2.13	11.20
D	2	3.54	2	2.1	6.25
E	2	4.19	6	9.05	12.55
F	2	3.35	10	19.11	7.62
G	2	4.74	6	9.02	13.20
H	2	4.01	1	1.06	13.12
I	2	3.11	10	19.14	20.00
J	2	2.24	6	9.17	8.64
K	3	3.88	2	2.07	13.84
L	2	0.71	9	16.2	5.12
M	2	2.54	2	2.16	8.56
N	2	3.72	6	9.09	11.75
O	3	3.82	9	16.08	8.30
P	3	2.16	3	6.18	8.36
R	2	2.67	4	7.15	10.22
S	2	3.35	5	8.12	9.78
T	2	4.53	7	15.03	11.08
U	2	4.48	6	9.04	7.89

3. “The Highest Value” Method

The algorithm for this method is as follows:

1) Depot is the initial current point
2) For each target, calculate total time needed to accomplish mission (Total time = Travel time + Service time)
3) For each target calculate its value. The value of the target is the ratio of the bonus point of the target to the total time of the target. (Value = Bonus Point / Total time)
4) Order all unvisited targets from highest value to lowest value
5) Go to the target that has the highest value
6) Calculate the available time

   [Available time = Endurance time - (∑Travel time + ∑ service time]

7) For each unvisited target calculate the required time

(Required time = Travel time from current point to the next target + Service time of the next target + Travel time from next target to the depot)

8) If required time of any unvisited target is less than the available time then order all targets with (required time) <= (available time) by value and go to step 5, else return to the depot

Table 4 shows the relevant information for the algorithm at step 1. The first column of Table 4 gives a symbolic letter of target name and the second column shows the bonus points of targets, which are assigned to represent the priority of the mission. Third column represents the mission duration time of the target (either two or three hours). The fourth column shows the travel time of a UAV to go from the depot to the related target shown in the first column. Next, total time needed to accomplish mission from current target to each unvisited target is calculated. The fifth column shows the total times. The bonus point of the target is divided by its total time in order to find its value, as shown in column six. After that, all targets are ranked according to their values, as seen in column seven. The UAV goes to the target that has the highest value. Then, the required time is calculated, as shown in column eight. Available time is the time left after accomplishing the mission. This process continues till available time is greater than any required time. If there is no available target to go to, the UAV returns to the depot. The same rules are followed for the other UAVs.

Table 4. An example of “The Highest Value” method (Putting targets in order when the UAV is at depot)

1	2	3	4	5	6	7	8
	Points	**Service Time**	**Travel Time**	**Total Time**	**Value**	**Rank**	**Required Time**
A	9	2	2.00	4	2.25	19	6.71
B	6	3	4.75	7.75	0.77	7	11.80
C	2	3	3.24	6.24	0.32	3	9.61
D	2	2	3.54	5.54	0.36	4	8.41
E	6	2	4.19	6.19	0.97	12	10.69
F	10	2	3.35	5.35	1.87	17	8.13
G	6	2	4.74	6.74	0.89	9	11.65
H	1	2	4.01	6.01	0.17	1	10.73
I	10	2	3.11	5.11	1.96	18	7.52
J	6	2	2.24	4.24	1.42	16	6.71
K	2	3	3.88	6.88	0.29	2	11.44
L	9	2	0.71	2.71	3.32	20	2.71
M	2	2	2.54	4.54	0.44	5	7.28
N	6	2	3.72	5.72	1.05	13	9.95
O	9	3	3.82	6.82	1.32	15	10.05
P	3	3	2.16	5.16	0.58	6	7.32
R	4	2	2.67	4.67	0.86	8	8.00
S	5	2	3.35	5.35	0.94	11	8.62
T	7	2	4.53	6.53	1.07	14	10.97
U	6	2	4.48	6.48	0.93	10	10.28

C. EXACT SOLUTION

As mentioned before, for increasing numbers of targets the number of possible solutions increases exponentially. At the beginning of the study, the authors tried to develop an algorithm to solve for the optimal solution for the case of 20 targets and three UAVs. Realizing that they could not find the exact solution using the Solver add-in in Microsoft Excel, they decreased the number of targets to 10 and UAVs to one so that they could solve for the exact solution. This enabled the authors to measure the relative value of their heuristic methods.

In the formulation of one UAV and 10 targets, the authors dealt with 1,036 constraints and 110 decision variables. It took approximately three seconds for Microsoft Excel Solver to solve the problem (on a 1.73 Ghz. processor pc). The authors solved 100 randomly generated problems using Solver and each of their three heuristic methods. They next compared the bonus points collected by the UAV.

Running the solver for 100 randomly generated instances showed an average of a 6% gap between “The Highest Value” heuristic method and the exact solution. For the instances developed for this study, this method found the optimum solution in 50 of the 100 cases. This heuristic gave the best results of all.

“The Highest Point” heuristic method found the optimum solution 39 out of 100 times and there is an average of a 10% gap between the heuristic and the exact solution results.

“The Closest” heuristic method found the optimum solution 11 out of 100 times and there is an average of a 24% gap between the heuristic and the exact solution. This method gave the worst results of all methods.

D. COMPUTATIONAL EXPERIMENT

For one problem, the results of “The Closest” method are given in Table 5. The program calculates the total collected bonus points, total time spent and total number of targets visited by the three UAVs. Figure 8 illustrates one of the solutions found by this heuristic.

Table 5. The results for “The Closest” method

1)		Available Time	Travel Time	Service Time	Time Left	Points
	L	20.00	0.71	2	17.29	9
	P	17.29	2.16	3	12.13	3
	M	12.13	0.82	2	9.31	2
	N	9.31	2.14	2	5.18	6
	Depot	5.18	3.72	0	1.45	0
2)		**Available Time**	**Travel Time**	**Service Time**	**Time Left**	**Points**
	A	20.00	2.00	2	16.00	9
	R	16.00	1.34	2	12.66	4
	H	12.66	1.93	2	8.73	1
	K	8.73	1.23	3	4.50	2
	Depot	4.50	3.88	0	0.62	0
3)		**Available Time**	**Travel Time**	**Service Time**	**Time Left**	**Points**
	J	20.00	2.24	2	15.76	6
	C	15.76	1.06	3	11.71	2
	S	11.71	0.93	2	8.77	5
	E	8.77	2.35	2	4.42	6
	Depot	4.42	4.19	0	0.23	0
Total	Time=	**53.50 hr**		Total	Points=	**55.00**
Targets	Visited=	**12**				

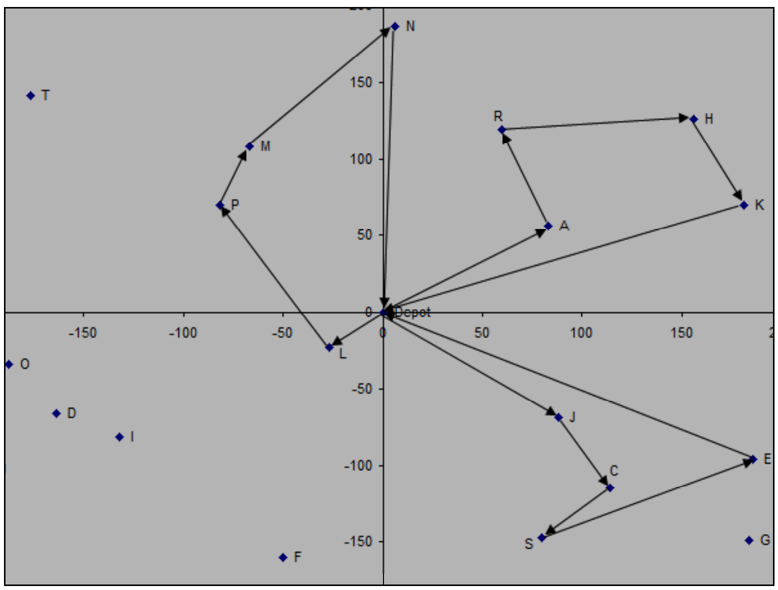

Figure 8. An example of a route planned by “The Closest” method

For one problem, the results of “The Highest Point” method are given in Table 6. The program calculates the total collected bonus points, total time spent and total number of targets visited by three different UAVs. Figure 9 illustrates one of the solutions found by this heuristic.

Table 6. The results for "The Highest Point" method

1)		Available Time	Travel Time	Service Time	Time Left	Points
	I	20.00	3.11	2	14.89	10
	F	14.89	2.26	2	10.63	10
	L	10.63	2.78	2	5.85	9
	Depot	5.85	0.71	0	5.14	0
2)		**Available Time**	**Travel Time**	**Service Time**	**Time Left**	**Points**
	A	20.00	2.00	2	16.00	9
	O	16.00	5.71	3	7.29	9
	D	7.29	0.80	2	4.49	2
	Depot	4.49	3.54	0	0.95	0
3)		**Available Time**	**Travel Time**	**Service Time**	**Time Left**	**Points**
	T	20.00	4.53	2	13.47	7
	N	13.47	3.77	2	7.71	6
	R	7.71	1.72	2	3.98	4
	Depot	3.98	2.67	0	1.32	0
Total	Time=	**52.59 hr**		Total	Points=	**66.00**
Targets	Visited=	**9**				

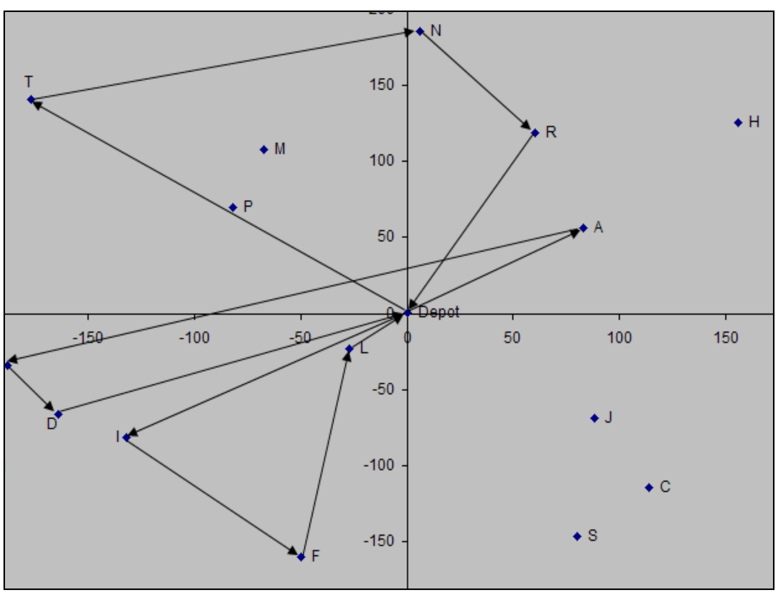

Figure 9. An example of a route planned by "The Highest Point" method

For one problem instance, the results of "The Highest Value" method are given in Table 7. The program calculates the total collected bonus points, total time spent and total number of targets visited by three different UAVs. Figure 10 illustrates one of the solutions found by this method.

Table 7. The results for "The Highest Value" method

1)		**Available Time**	**Travel Time**	**Service Time**	**Time Left**	**Points**
	L	20.00	0.71	2	17.29	9
	I	17.29	2.41	2	12.88	10
	F	12.88	2.26	2	8.62	10
	J	8.62	3.31	2	3.31	6
	Depot	3.31	2.24	0	1.08	0
2)		**Available Time**	**Travel Time**	**Service Time**	**Time Left**	**Points**
	A	20.00	2.00	2	16.00	9
	R	16.00	1.34	2	12.66	4
	N	12.66	1.72	2	8.94	6
	P	8.94	2.91	3	3.02	3
	Depot	3.02	2.16	0	0.87	0
3)		**Available Time**	**Travel Time**	**Service Time**	**Time Left**	**Points**
	O	20.00	3.82	3	13.18	9
	U	13.18	1.40	2	9.78	6
	B	9.78	0.50	3	6.28	6
	Depot	6.28	4.75	0	1.53	0
Total	Time=	**56.53** hr		Total	Points=	**78.00**
Targets	Visited=	**11**				

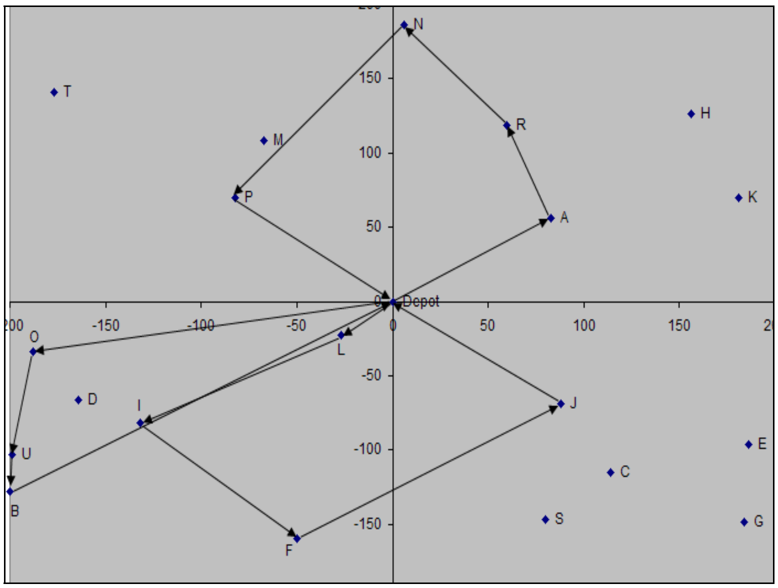

Figure 10. An example of a route planned by “The Highest Value” method

The authors ran the program 100 times with 20 targets for each method and compared the results of these three heuristics to each other. “The Highest Value” method performed much better than the other two methods based on the test problem. “The Highest Value” method collected the highest point for 91 times, while “The Highest Point” method reached to the best score 17 times and “The Closest” method did the best for only four times. Then the authors ranked the algorithms according to the bonus points collected. For each instance the heuristic that achieved the best solution was given a 1, the next best heuristic a 2, and the worst heuristic a 3. In the case of a tie, both heuristics were given the same rank. Average rank of “The Highest Value” method was 1.10, while average rank of “The Highest Point” method was 2.04 and average rank of “The Closest” method was 2.70. The available bonus point was calculated by summing the bonus points of all 20 targets. The bonus point ratio is the ratio of the total collected bonus points to the available bonus points. For the average bonus points ratio of the 100 trials, “The Highest Value” method gave the best results with a score of 0.69. Table 8 presents the comparative results of the three heuristic methods. “The Highest Value” method had better results in terms of collecting bonus points, but visited fewer targets. This method visits 10.57 targets on average while “The Closest” visits 11.59. This indicates that having accurate priority information is essential. The second best method was “The Highest Point” method, but the results were relatively non-satisfactory.

Table 8. Comparison of three heuristic methods

	Highest Value	**Closest**	**Highest Point**
Best or tied for best	91	4	17
2nd	8	22	62
3rd	1	74	21
Average rank	1.10	2.70	2.04
Average point ratio	0.69	0.57	0.63
Average total time	56.25	52.55	55.72
Average targets visited	10.57	11.59	8.97

Since the endurance time of a UAV is 20 hours, total time flown by three UAVs can be a maximum 60 hours. Using the authors' three methods, the average total time flown by three UAVs can be seen in Table 8. The authors also calculated the average visited targets by three UAVs over 100 trials. On average, the UAVs visited 11.59 targets with "The Closest" method, while they visited 10.57 targets with "The Highest Value" method and 8.97 targets with "The Highest Point" method.

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V. CONCLUSIONS AND RECOMMENDATIONS

A. SUMMARY AND CONCLUSIONS

UAVs are force multipliers for the operational commanders and significantly increase a combatant or joint force commander's ability to succeed at strategic, operational, and tactical objectives. Today, UAVs are increasingly used in combat situations and their importance in future warfare will continue to grow. UAVs are also likely to become more important in many different civilian applications. This increasing importance of UAVs raises the question of efficient usage and the route planning of UAVs is the most critical and challenging problem of wartime in terms of efficiency.

This research focused on the effective use of UAVs in terms of planning and scheduling. Three different heuristic methods were offered for the route planning of three identical UAVs. The battlefield was assumed to be a two-dimensional plane and UAVs had constant speed during the flight. The heuristics that were given in this thesis sought to maximize the bonus points of the computationally generated targets, which had a random location, random bonus point value, and a random mission type of either two or three hours. The bonus points here were assigned to represent the priority of the mission. The heuristics developed by the authors are “The Highest Point,” “The Closest,” and “The Highest Value” algorithms. Essentially, “The Highest Point” is a greedy algorithm considering the bonus point values. “The Closest” heuristic method is a greedy algorithm considering distance. Different from the first two algorithms, “The Highest Value” is a weighted greedy heuristic considering the bonus points per distance value. These heuristics produced the schedule incrementally, choosing the next point at each stage by looking at the vertices remaining to be scheduled. In the previous chapters the authors discussed the results and analysis of these heuristics and measured these operational objectives with respect to the priority of the missions.

The computational experiments of 100 instances proved that there is still an average of 6% gap between the possible best route and the best heuristic algorithm, “The Highest Value.” Over 100 instances, “The Highest Value” method gave the best result of all three methods 91 times. “The Highest Point” method gave the best result 17 times. Only for one instance did “The Closest” method maximize the collected bonus points. “The Highest Value” and “The Highest Point” methods concluded the same path 11 times. However, “The Highest Point” and “The Closest” methods revealed an average gap of 10% and 24%, respectively, when compared with the exact solution

Considering the fact that the armed forces require continuous intelligence and updated data, within a reasonable time after collecting said data, to find, track, and assess the opposing forces, the right intelligence at the right time is necessary. Therefore, if a UAV fleet available to collect necessary intelligence, and if a most valuable asset is used more efficiently, then due to such strength you become stronger and have more chance to survive. This study confirmed the importance of the mission planning method in the use of UAVs. Our algorithms kept three different policies to plan the mission and we reached three different levels of satisfaction, which will directly affect success during war.

B. RECOMMENDATIONS FOR FUTURE WORK

The authors attempted to include as many factors as possible into the model to create a more realistic scenario. However, many more factors could be taken into consideration. An analyst with real-life data or more instances with sophisticated computerization and a more advanced software package could extend the realistic outputs of the model. Including more aerial vehicles or mission types will add to the realism.

There are many more constraints on aerial operations in real life. The strategic deployment of ground stations, the range and the capacity of remote controlling, readiness level of personnel and equipment, and the strategic level of the decision-making process may significantly affect the most convenient path planning of UAV missions. The use of more sophisticated software might extend the scope of the study.

Generally, fuel is the limiting factor in aerial vehicles' endurance times, and altitude directly affects fuel flow. On the other hand, some missions require low altitude to get more detailed imagery, while others require high altitude for fuel efficiency, longer endurance, and persistent intelligence. This study can be expanded into a three-dimensional case study by having different mission altitudes with different fuel flow rates, or by including the climbing and descending delays of the vehicles. In a broader perspective, the model also can be applied in the same manner to a 3D simulation map.

Applying more complex heuristic models, mentioned in Chapter III, may find better results. The applications of the MTMPC problem are very broad and varied in the trade market. Extending the scope to those market applications and including a literature review of current solutions and comparing the results may introduce a better study.

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